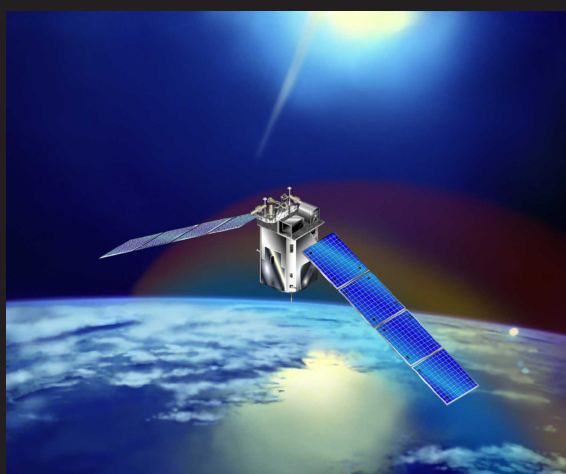
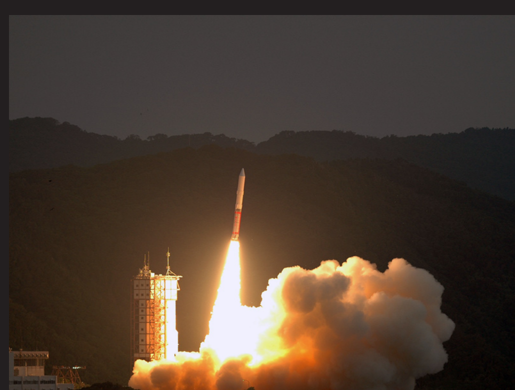
National Aeronautics and Space Administration

NASA Engineering Design Challenge
EnginVision – Rockets





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Living With a Star Program
Solar Terrestrial Probes Program
NASA Goddard Space Flight Center, Greenbelt, MD

NASA Engineering Design Challenges

Overview

Connect to Engineering and Science

The Engineering Design Challenges connect students with the work of NASA engineers by engaging them in related design challenges of their own. With some simple and inexpensive materials, you can lead an exciting unit that focuses on a specific problem that NASA engineers must solve and the process they use to solve it. In the classroom, students design, build, test, and revise their own solutions to problems that share fundamental science and engineering issues with the challenges facing NASA engineers.

The Design Challenge

Students will build an air pressure launcher and a model rocket. The model rocket should be as light as possible yet strong enough to withstand the load of a "launch to orbit " three times.

Students first determine with different variables the amount of force needed to launch the model rocket. Then they design, build, and test their own structure designs. They revise their designs over several design sessions, trying to maintain or increase the strength and reduce the weight of their structure to determine which variables give the rocket the best or farthest distance down range. They document their designs with sketches and written descriptions. As a culmination, students compile their results into a poster and present them to the class.

Time Required

The design challenge can be carried out in six 45-minute class periods, but you could easily extend it for twice that long.

You will need to invest 4-8 hours gathering the materials, building the test stand, trying out your own designs, reading the guide, and preparing the classroom.

Value to Students

These activities help students achieve national goals in science, math, and thinking skills. In the pilot testing of the design challenge, students embraced the design challenge with excitement. The value of this activity to your students is the opportunity to solve a challenge based on a real-world problem that is part of the space program and to use creativity, cleverness, and scientific knowledge in doing so. Students have many opportunities to learn about forces, structures, and energy transfer during the activities. The culminating activity gives students an opportunity to develop their presentation and communication skills.

Student Research Opportunities

The Resources section of this guide includes many web sites where students can obtain additional information.

Parent Involvement

The Masters section of this guide includes a reproducible flyer to send home to inform parents about the activity and includes suggested activities students and parents can do at home together.

Safety

These activities meet accepted standards for laboratory science safety.

How to use this guide

This guide is divided into several sections:
• National Science Education Standards
• Math Connections
• Thinking Skills
• Background material
• Preparation for the challenge
• Day-by-day procedures
• Extensions
• Resources
• Masters

National standards

If you have questions about how this activity supports the national science education standards, math connections, and thinking skills, read these sections that follow immediately. Otherwise, refer to those sections as you need them.

Suggested order of reading

First, skim through the entire guide quickly to see what is included.

Next, read through the Classroom Sessions that describe what happens in each of the six sessions. Give special attention to the last part: “Linking Design Strategies and Observations to Science Concepts.” This gives explicit suggestions on how to help students understand the science in their designs. Review this section once you start classroom work with your students.

Be sure to read the last two sections in the Teacher Preparation section: “Teaching Strategies for an Engineering Design Challenge” and “Helping Students Understand the Design Process.” These will help you understand what is distinctive about an engineering design challenge and how your students can get the most out of it.

When you understand the session-by-session flow and the pedagogical approach on which it is based, read the Background section. This will provide you with information you will want to have in mind to “set the stage” for students and to link their classroom work with the work of NASA engineers. It focuses on one of the challenges faced by NASA engineers in developing a reusable launch vehicle: spacecraft structures.

Further resources for you and your students can be found in the Resources section.

The reproducible masters you need are in the Masters section.

Finally, read the remainder of Teacher Preparation to find out how to prepare your classroom and yourself to conduct the engineering design challenge. It contains safety guidelines, lists of materials, suggestions for organizing the classroom, and teaching techniques.

National Science Education Standards

This Engineering Design Challenge supports the following Content Standards from the National Research Council's National Science Education Standards.

Science as inquiry

All students should develop abilities necessary to do scientific inquiry.

Fundamental abilities and concepts

- Students should develop general abilities, such as systematic observation, making accurate measurements, and identifying and controlling variables
- Students should use appropriate tools and techniques, including mathematics, to gather, analyze, and interpret data
- Students should base their explanation on what they observed; providing causes for effects and establishing relationships based on evidence
- Students should think critically about evidence, deciding what evidence should be used and accounting for anomalous data.
- Students should begin to state some explanations in terms of the relationship between two or more variables
- Students should develop the ability to listen to and respect the explanations proposed by other students
- Students should become competent at communicating experimental methods, following instructions, describing observations, summarizing the results of other groups, and telling other students about investigations and explanations
- Students should use mathematics in all aspects of scientific inquiry

All students should develop understandings about scientific inquiry.

Fundamental abilities and concepts

- Students should develop general abilities, such as systematic observation, making accurate measurements, and identifying and controlling variables
- Mathematics is important in all aspects of scientific inquiry
- Technology used to gather data enhances accuracy and allows scientists to analyze and quantify results of investigations
- Scientific explanations emphasize evidence
- Scientific investigations sometimes generate new procedures for investigation or develop new technologies to improve the collection of data

Physical science

All students should develop an understanding of motions and forces.

Fundamental concepts and principles, grades 5-8

- An object that is not being subjected to a force will continue to move at a constant speed and in a straight line.
- If more than one force acts on an object along a straight line, then the forces will reinforce or cancel one another, depending on their direction and magnitude. Unbalanced forces will cause changes in the speed or direction of an object's motion.
- Energy is transferred in many ways.

Fundamental concepts and principles, grades 9-12

- Objects change their motion only when a net force is applied. Laws of motion are used to calculate precisely the effects of forces on the motion of objects. The magnitude of the change in motion can be calculated using the relationship F=ma, which is independent of the nature of the force. Whenever one object exerts a force on another, a force equal in magnitude and opposite in direction is exerted on the first object.

Science and technology

All students should develop abilities of technological design.

Fundamental concepts and principles

1. Design a solution or product
    a. Consider constraints
    b. Communicate ideas with drawings and simple models
2. Implement a design
    a. Organize materials
    b. Plan work
    c. Work as collaborative group
    d. Use suitable tools and techniques
    e. Use appropriate measurement methods
3. Evaluate the design
    a. Consider factors affecting acceptability and suitability
    b. Develop measures of quality
    c. Suggest improvements
    d. Try modifications
    e. Communicate the process of design
    f. Identify stages of problem identification, solution design, implementation, evaluation

The challenge satisfies the following criteria for suitable design tasks:

- Well defined, not confusing
- Based on contexts immediately familiar to students
- Has only a few well-defined ways to solve the problem
- Involves only one or two science ideas
- Involves construction that can be readily accomplished by students, not involve lengthy learning of new physical skills, not require timeconsuming preparation or assembly

All students should develop understandings about science and technology.

- Difference between scientific inquiry and technological design
- Technological designs have constraints
- Technologies cost, carry risks, provide benefits
- Perfectly designed solutions don’t exist; engineers build in back-up systems

Background

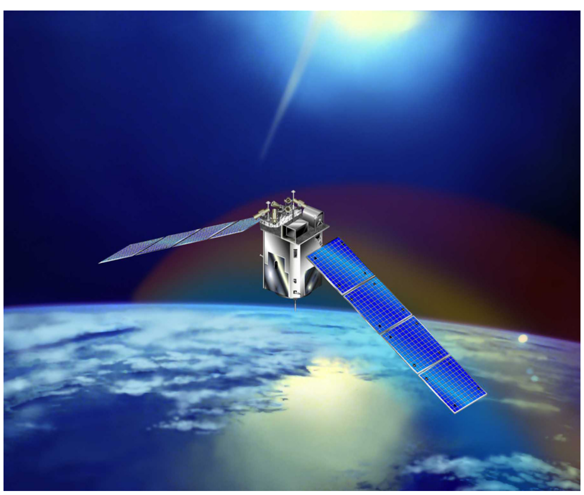
TIMED, STEREO & Solar-B

TIMED

What is TIMED and its purpose?

TIMED is an acronym for Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics. The TIMED mission is studying the influences of the sun and humans on the least explored and understood region of Earth's atmosphere – the Mesosphere and Lower Thermosphere/Ionosphere (MLTI). TIMED is focusing on a portion of this region located approximately 40-110 miles (60-180 kilometers) above Earth's surface.

The science objective of the TIMED mission is to understand the MLTI region's basic pressure, temperature and wind that result from the transfer of energy into and out of this region. This mission is helping scientists gain a better understanding of the dynamics of this gateway region and its effects on communications, satellite tracking, spacecraft lifetimes, degradation of spacecraft materials and on spacecraft reentering Earth's atmosphere.



What will TIMED accomplish that other spacecraft have not?

TIMED is the first mission to conduct a comprehensive global study of this region, including its basic structure and thermal balance, how the mesosphere is coupled to the thermosphere/ionosphere, how the MLTI region is coupled to space and the lower atmosphere below, and how energy is transported vertically and horizontally through this region. The TIMED mission is establishing a baseline against which future studies of changes within this region can be compared and analyzed.

How does TIMED fit into NASA's overall science program?
The Sun-Earth Connection (SEC) is one of four principal science themes around which missions within NASA's Office of Space Science are organized. The Sun-Earth Connection focuses largely on explaining the physical processes that link the sun and the Earth. TIMED is the first mission within the Solar Terrestrial Probes Program, which falls under the SEC theme. It is investigating one of the Sun-Earth Connection's quests: How does the Earth's upper atmosphere respond to solar inputs?

The Solar Terrestrial Probes Program offers a continuous sequence of flexible, cost-capped missions designed to systematically study the Sun-Earth system. Solar Terrestrial Probes missions focus on studying the sun and the Earth as an integrated system using a blend of in situ and remote-sensing observations, often from multiple platforms.

Where is the MLTI atmospheric region located, and why is it important to study this region?
The portion of the MLTI (Mesosphere and Lower Thermosphere/Ionosphere) region that TIMED is studying is located approximately 40-110 miles (60-180 kilometers) above Earth's surface. This region is where the sun's energy is first deposited into Earth's environment. The sun's energy can have profound effects on Earth's upper atmospheric regions, particularly during the peak of the sun's 11-year solar cycle when the greatest amounts of its energy are being released. TIMED is focused on understanding and characterizing exactly how the sun interacts with the Earth's environment. It will allow scientists to establish the first-ever baseline of the MLTI region against which future studies of changes within this region can be compared and analyzed.

Why have studies of this region been limited?
A comprehensive global study of the entire MLTI region has never before been accomplished for several reasons. Ground-based instruments can only see a small portion of the upper atmosphere located over an observation site. It's too high for balloons to reach. Sounding rockets (rockets that fly into the upper atmosphere for just a few minutes before falling back

down) can only provide a brief snapshot of the MLTI region's activity near the rocket.

How will TIMED provide the first-ever global picture of the MLTI region?

The TIMED spacecraft is observing the MLTI region and its basic structure from the spacecraft's 388-mile (625-kilometer) circular orbit around the Earth. Employing advances in remote-sensing technology, the spacecraft's instrument suite is working with a worldwide network of ground-based observation sites to collect information necessary for scientists to test their current understanding of the processes that change the wind and composition in this part of the atmosphere, and determine how energy is absorbed, emitted and transported within the MLTI region.

How many and what types of instruments are onboard the spacecraft?

TIMED's payload consists of four instruments. The Global Ultraviolet Imager (GUVI) is a spatial-scanning, far-ultraviolet spectrograph designed to globally measure the composition and temperature profiles of the MLTI region, as well as its auroral energy inputs. The Solar Extreme Ultraviolet Experiment (SEE) is comprised of a spectrometer and a suite of photometers designed to measure the solar soft X-rays, extreme-ultraviolet and far-ultraviolet radiation that is deposited into the MLTI region. The TIMED Doppler Interferometer (TIDI) is designed to globally measure the wind and temperature profiles of the MLTI region. And a multichannel radiometer known as SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) is designed to measure heat emitted by the atmosphere over a broad altitude and spectral range, as well as global temperature profiles and sources of atmospheric cooling.

Who has access to TIMED data and how is it distributed? How quickly is data made available?

Data obtained during the TIMED mission is available to the public and accessible through TIMED's Web site (http://www.timed.jhuapl.edu).

TIMED's distributed data management approach enables rapid turnaround of data products available for distribution. Total turnaround time – from the spacecraft acquiring data to development of a final product and its distribution online – is within 54 hours. Traditionally, a mission could take up to several days or weeks to get similar products distributed.

When, and from where, was the spacecraft launched?
The TIMED spacecraft was boosted into its 388-mile (625-kilometer) circular orbit around the Earth (inclined 74.1 degrees from the equator) aboard a Delta II 7920-10 launch vehicle from Vandenberg Air Force Base, Calif., on Dec. 7, 2001. The 1,294-pound (587-kilogram) spacecraft rode aboard a Delta II with the Jason-1 spacecraft — a joint project between NASA's Jet Propulsion Laboratory, in Pasadena, Calif., and the U.S. and French space agencies.

How long will the mission last?
The TIMED spacecraft will collect data, while in orbit around the Earth, for two years. An additional two years of data analysis will be supported by TIMED's Mission Operations and Science Data centers, located at The Johns Hopkins University Applied Physics Laboratory in Laurel, Md.

What are the key characteristics of the spacecraft?

- Mass: 1,294 pounds (587 kilograms)
- Dimensions
    - o 8.93 feet (2.72 meters) high
    - o 5.29 feet (1.61 meters) wide (launch configuration)
    - o 38.5 feet (11.73 meters) wide (solar arrays deployed)
    - o 3.93 feet (1.2 meters) deep
- Power Consumption: 406 watts per orbit
- Data Downlink: 4 megabits per second
- Memory: 5 gigabits
- Attitude
    - o Control - Within 0.5 degrees
    - o Knowledge - Within 0.03 degrees

STEREO

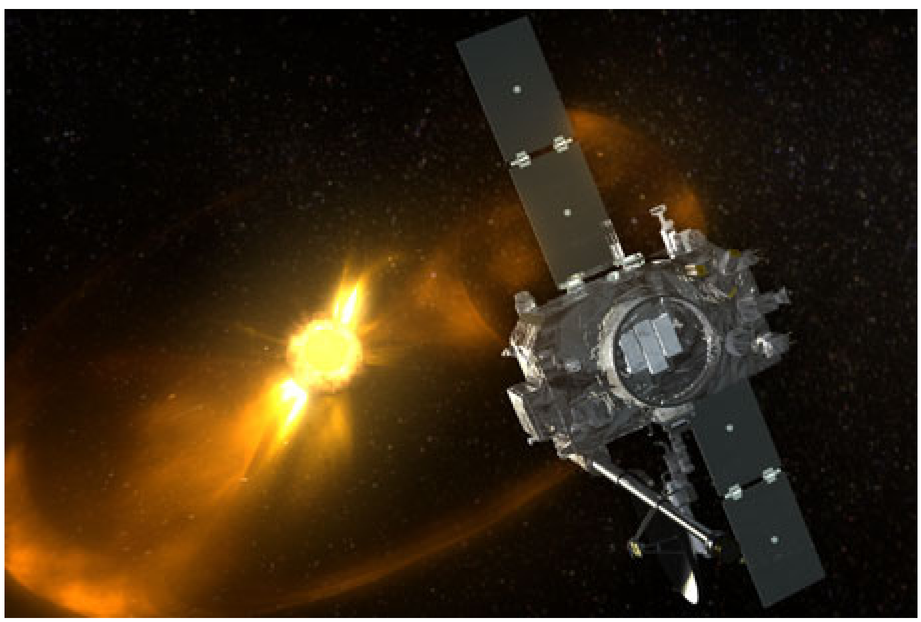
STEREO Views of the Sun

STEREO is a 2-year mission employing two nearly identical spacebased observatories to provide the first-ever, 3-D “stereo” images of the sun to study the nature of coronal mass ejections. These powerful solar eruptions are a major source of the magnetic disruptions on Earth and a key component of space weather, which can greatly affect satellite operations, communications, power systems, the lives of humans in space, and global climate.

STEREO is the third mission in NASA’s Solar Terrestrial Probes Program. The twin observatories are scheduled to launch aboard a single Boeing Delta II rocket from Cape Canaveral Air Force Station, Fla., in fall 2006.

Capturing the Sun in 3-D

The twin observatories will fly as mirror images of each other to obtain unique “stereo” views of the sun’s activities. They must



be placed into a rather challenging orbit where they’re offset from one another. One observatory will be placed ahead of Earth in its orbit around the sun and the other behind. Just as the slight offset between your eyes provides you with depth perception, this placement will allow the STEREO observatories to obtain 3-D images and particle measurements of the sun.

Placing STEREO into Orbit
STEREO mission designers determined that the most efficient and cost-effective way to get the twin observatories into space was to launch them aboard a single rocket and use lunar swingbys to place them into their respective orbits. This is the first time lunar swingbys have been used to manipulate orbits of more than one spacecraft. Mission designers will use the moon's gravity to redirect the observatories to their appropriate orbits – something the launch vehicle alone can't do.

After launch, the observatories will fly in an orbit from a point close to Earth to one that extends just beyond the moon. Approximately two months later, mission operations personnel at the Johns Hopkins University Applied Physics Laboratory (APL), in Laurel, Md., will synchronize spacecraft orbits, directing one observatory to its position ahead of Earth in its orbit. Approximately one month later, the second observatory will be redirected to its position trailing Earth.

Seeing with STEREO
Each twin STEREO observatory will carry two instruments and two instrument suites. This combination provides a total of 16 instruments per observatory. APL is designing and building the spacecraft platform housing the instruments. When combined with data from observatories on the ground or in space, STEREO's data will allow scientists to track the buildup and liftoff of magnetic energy from the sun and the trajectory of Earth-bound coronal mass ejections in 3-D.

Observatory Design
Sun Earth Connection Coronal and Heliospheric Investigation (SECCHI)

- Studies 3-D evolution of coronal mass ejections (from their origin on sun's surface to their impact at Earth)
- Principal Investigator: Russell Howard, Naval Research Laboratory, Washington, D.C.

In situ Measurements of PArticles and CME Transients

(IMPACT)
- Measures energetic ions and electrons accelerated in coronal mass ejection shocks and in solar flares
- Principal Investigator: Janet Luhmann, University of California, Berkeley

PLAsma and SupraThermal Ion and Composition (PLASTIC)
- Studies coronal-solar wind and solar wind-heliospheric processes
- Principal Investigator: Antoinette Galvin, University of New Hampshire

STEREO/WAVES (S/WAVES)
- Tracing the generation and evolution of traveling radio disturbances from the sun to Earth's orbit
- Principal Investigator: Jean-Louis Bougeret, Paris Observatory, Meudon

Launch Configuration

A spacecraft separation system allows one STEREO observatory to sit atop the other within the third stage of the Delta II launch vehicle.

Solar-B – Hinode

The next generation solar observatory launched in September of 2006. Are ou ready for a new look at the Sun?

Mission

Solar-B is a mission of the Japan Aerospace Exploration Agency (JAXA) in collaboraion with NASA and PPARC (United Kingdom). It follows the successful Yohkoh (Solar-A) mission.

Solar-B launched from Kagoshima, Japan in September 2006. It will ride an M-V rocket into the polar, Sun-synchronous orbit 600 kilometers above the Earth's surface, where it will spend three years almost continuously observing the Sun.

Goals

- Understand the creation and destruction of the Sun's magnetic fields
- Understand solar eruptions and the solar wind

- Understand the variability of the Sun’s luminosity
- Understand the generation of ultraviolet and x-ray radiation

Spacecraft
Optical Telescope – 0.5-meter diameter primary mirror
Mass – 900 kg
Power – 1100 W (two single-axis solar arrays)
Telemetry – 4 Mbps for 10 minute playback, 13-17 passes per day
Data Recorder – 8 Gbit (solid state)
Attitude – Skewed momentum wheel system
Stability – 1 arcsecond (spacecraft); 0.02 arcsecondso ver 10s through tip/tilt mirror (SOT)
Communications – X Band, S Band

Rockets

Delta II

Boeing Delta II rockets can be configured into two-or three-stage vehicles to accommodate a variety of mission requirements.

Payload Options

Vehicles can launch single, dual, or multiple payloads on the same mission. Payload options include:

- Delivery of 900 to 2,170 kg (1,980 to 4,790 lb) payloads into a geosynchronous transfer orbit (GTO)
- Delivery of 2.7 to 6.1 metric tons (5,960 to 13,440 lb) to low-Earth orbit (LEO)
- Various payload attach fittings
- Various fairing sizes to enclose and protect payloads:
  - Composite 3-meter (10-feet) diameter
  - Aluminum 2.9-meter (9.5-feet) diameter
  - Stretched composite 3-meter diameter

First-Stage Capabilities and Components

- All first-stage power options include the Rocketdyne RS-27A main engine
- For additional boost during liftoff, the first stage can be configured for three, four, or nine strap-on graphite epoxy motors (GEMs), depending upon requirements
  - When three or four GEMs are used, all are ignited at liftoff
  - When nine GEMs are used, six are ignited at liftoff, three are lit during flight

Second-Stage Capabilities and Components

The second stage usually delivers payloads into LEO and includes the following:

- Aerojet AJ10-118K second-stage engine
- Storable propellant with restart capability
- Navigation functions (guidance and control) for precise payload deployment, including a redundant inertial flight control assembly (RIFCA)

Third-Stage Option
A third stage is usually required for GTO, space exploration and planetary missions. The third stage utilizes a Thiokol Star-48B solid rocket motor

Information came from the Boeing website, for more information on launch systems see website http://www.boeing.com/defense-space/space/bls/index.html.

M-V Rocket

The M-V rocket, also called M-5 or Mu-5, was a Japanese solid fuel rocket designed to launch scientific satellites. It was a member of the Mu family of rockets. The Institute of Space and Astronautical Science (ISAS) began developing the M-V in 1990 at a cost of 15 billion yen. It has three stages and is 30.7 meters high, 2.5 meters in diameter, and weighs about 140 tonnes (310,000 pounds). It was capable of launching a satellite weighing 1.8 tonnes (2 short tons) into an orbit as high as 250 km (155 miles).

The first M-V rocket launched the HALCA radio astronomy satellite in 1997, and the second the Nozomi Mars explorer in July 1998. The third rocket attempted to launch the Astro-E X-ray satellite on February 10, 2000 but failed.

ISAS recovered from this setback and launched Hayabusa to 25143 Itokawa in 2003.

The following M-V launch was the scientific Astro-E2 satellite, a replacement for Astro-E, which took place on July 10, 2005.

The final launch was that of the Solar-B spacecraft, along with the SSSat microsat and a cubesat, HIT-SAT, on 22 September 2006.

Questions for class discussion or homework

1. Why is it important to make the reusable launch vehicle as lightweight as possible?

2. What is the STEREO, TIMED & Solar-B?

3. What are NASA engineers trying to do with TIMED, STEREO & Solar-B?

4. It costs $10,000 to lift a pound of payload into orbit aboard the Space Shuttle. Calculate the cost of sending yourself into space. How much would it cost to send yourself and your family and pets into space?

Answers to questions for class discussion or homework (Reference background section pg 10-19)

Teacher Preparation

In order to prepare yourself and your classroom for this engineering design challenge, you should:

- Use the Background Information section of this guide, as well as the Engineering Design Challenge web site to familiarize yourself with spacecraft structures used by NASA and the science and engineering concepts you will be introducing.
- Read through the day-by-day activities in the following section of this guide
- Gather the required materials
- Build the launcher
- Build the test rockets
- Practice the test procedure with your own designs
- Prepare the materials for the classroom
- Set up the classroom
- Organize students in teams
- Review safety procedures

Build the Launcher

Materials Needed

Rulers
Pencils
Rocket forms (short lengths of ½” PVC tubes)
Launcher (see photos for parts & assembly)

- Snap in Tubeless Tire Valve (TR418)
- 3 inch end cap
- 3 inch PVC Pipe (need 1 – 17, 6, & 5 inch pieces)
- ¾ inch PVC Pipe (need 2 – 2 inch pieces)
- ½ inch PVC Pipe (need 1 – 18 inch long piece)
- 3 inch 90 degree Elbow (need 2)
- 3 x 2 inch Coupling
- 2 x 1 ½ inch Flush Bushing
- 1 ½ x 1 inch Bushing
- 1 x ¾ inch Flush Bushing
- ¾ inch Ball Valve
- ¾ inch 90 degree Elbow (need 2)
- ¾ inch threaded nipple (this is a metal piece)
- ¾ x ½ inch flush bushing
- Primer & Cement Handi Pack

Tools

- PVC Cutter or Saw (miter box recommended)
- Pliers
- Drill
- 3/8 or ½ drill bit depending on size of tire valve
- Newspaper or butcher paper
- Latex gloves

Electric air compressor or hand pump with pressure gage
100 foot tape measure
Safety glasses for the launch

Time Needed

- Before Class – The launcher will require 1-2 hours to construct.
- Class – Constructing the rockets will take about ½ hour
- Launching and tracking the rockets will take about 1 hour
- Calculating the distance the rocket traveled (down range)

Construction

The air pressure launcher is made from Schedule 40 PVC plumbing parts available at most hardware stores. Refer to the diagrams for the specific parts needed. Clerks at the hardware store can help select the parts for you from the diagrams. Be sure to get pressure rated pipes for the 3”, ¾”, and ½” tubing (Note: tubing may only be sold in 8 – 10 foot lengths).

Using a saw, cut three pieces from the 3” pipe. The pieces should be 17, 6, and 5 inches long. PVC cuts very easily. Remove any burrs from the cut with sand paper and clean the pipe if it is dirty. Lightly sand outside ends of pipe approximately 1 ½ inch down. Cut ¾ inch pipe into two 2 inch segments. Take burrs off and sandpaper also. Cut an 18 inch long piece of the ½ inch pipe. Clean and sand ends (Note: sanding ensures better glue adherence).

Using a drill and bit, drill a hole into the center of the 3” end cap. The size of the hole will depend upon the diameter of the tire valve stem (3/8 to ½ inch). The hole should be just smaller than the diameter of the rubber stem so that the stem seals itself to the cap when it is pushed through the hole from the inside out. (NOTE: Moisten valve stem before putting in hole.) Use pliers to help pull tire valve through hole in end cap to seal properly but don’t apply too much pressure or you will crush tire valve.

Join the end cap to the 17-inch long 3” pipe segment with PVC cement. First clean both joining surfaces with PVC Purple Primer Cleaner. Make sure you are working in a well ventilated area away from open flame. When dry, coat the surfaces with PVC cement and push the parts together immediately. Following the same cementing procedure, join one elbow to the other end of the pipe. Next, join the 5-inch long 3” pipe to the elbow. Join the remaining large elbow to the other end of this pipe segment. Be sure that both elbows are aimed in the same direction. The large tubes will serve as the launcher base and the piece must not be twisted or the launcher will rock when it is being used. To insure proper alignment, set the base on the floor before the glue has set and press the second elbow until it is properly aligned.

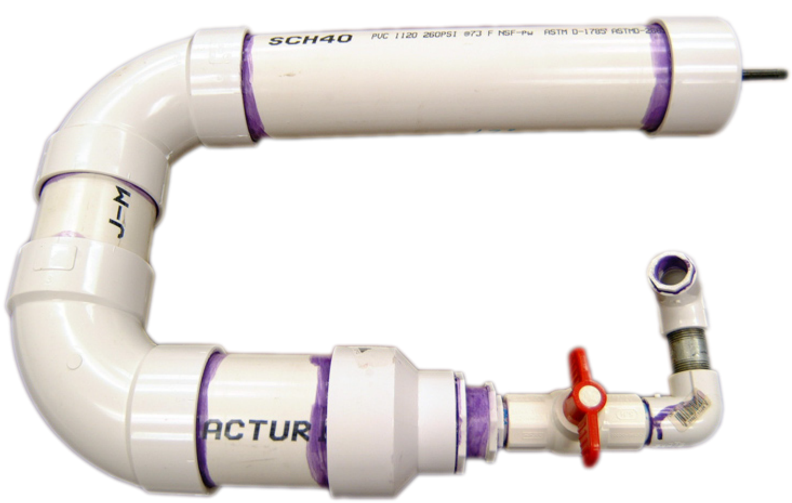
Cement the 6-inch long 3” pipe to the elbow.

Attach the 3” x 2” coupling and the 2 x ½ inch flush bushing followed by 1 ½ x 1 inch flush bushing and followed by 1 x ¾ inch flush bushing.

Prime & cement ball valve and the two ¾ inch pipe segments (one on each end). Cement this to the 3 x 2 inch coupling.

Thread nipple to 3 inch elbow Glue elbow to 3 inch pipe segment ball valve. Glue ¾ inch to ½ flush bushing to ¾ inch 90 degree elbow. (NOTE: make sure they are parallel to floor). Attach assembled elbow to threaded nipple but don’t over tighten. Attach the 18 inch long ½ inch pipe to end. Launch tube is adjustable elevation. (NOTE: optional to glue this piece)

Tip: To make it easer to slip rockets on the launch tube, use a file or sand paper to taper the upper end of the launch tube.



Build the Rockets

Use the instruction sheet for constructing the paper rockets. Have your students roll paper around the short lengths of ½” PVC tube. The tubes serve as forms for constructing the rockets. For best performance, the paper should be snug on the form but able to slide easily. Make sure students firmly attach the fins and nose cone for their rockets. Poorly attached nose cones will blow off the rocket, leaving the rocket behind. Poorly made rocket bodies may explode into confetti while on the launch pad.

An example to build your own Rocket

Matierials needed

Soda bottles (and caps)
You will use the one-liter size for most of the rockets, but it is good to have on hand some two-liter bottles as well. The bottles that have a 5-lobe base is better for this activity than other kinds.

Brass launch tubes
Craft, art supply, and hobby stores sell brass tubing in sizes that just fit inside each other, so it is sometimes called “telescoping tubing.” It comes in 12-inch lengths. 9/16 inch outside diameter is just right to fit easily over the launch rod (the ring stand). You’ll need to cut the tube into 4-inch lenghts, which you can do with a tubing cutter or a fine saw.

Package tape
This is used to attach the launch tube to the soda bottle.

Construction
Fill the bottle with water and cap it tightly. Tape a 4-inch length of tube to the flat cylindrical part of the bottle. Be sure that tube is vertical.

Practice Launching a Rocket

Once you have constructed the launcher and rockets, you will want to try some models yourself to become familiar with adjusting the launcher and assuring consistent test conditions.

1. Select a clear field for the launch. Caution: Although the rockets are made of paper, they can still cause injury, if someone is struck by them.

2. Set up the launcher and orient the base so that the launch tube can point straight upward. If the wind is blowing, you will want to aim the angle of the tube slightly into the wind.

3. Connect the air compressor or hand pump to the tire valve on the launcher. With the valve closed, pump the launcher up to 30 pounds of pressure. Observe how far the rocket goes and in which direction. Make adjustments to aiming and pump the launcher to 50 pounds of pressure. Again, test fire a rocket and make any final aiming adjustments.

4. Load the rocket on the launch rod. Clear the landing site from bystanders.

5. Perform a count down. If you will be determining how high the rocket fires, this lets trackers know when the rocket is about to launch.
6. Let only the builder of the rocket fetch it after it lands.

TIP: Some teachers have reported better flight performance with low-pressure launches than with high-pressure launches. Aerodynamic drag on the rocket increases with velocity. At higher initial velocities, rocket fins may be distorted, leading to even greater drag and diminished performance. How can students test this theory?

Safety Rules

Do not pump the launcher up to a pressure greater than half the rated pressure of the weakest part. The PVC pipes and the valve come with pressure ratings. If the lowest rating is 150 psi, do not pressurize the launcher to greater than 75 psi. This provides a significant safety margin.

Be careful in handling the launcher. PVC can crack if dropped or struck with sufficient force. Inspect the launcher before use. Discard a launcher that shows signs of cracking.

- **Do not lean over the launcher rod at any time.**
- **Do not place anything inside the launcher rod.**
- **Wear eye protection for launches.**

Prepare the Materials for the Classroom

You may wish to assemble the materials into kits before distributing them to students. In this way you can reduce the amount of time spent on distributing materials. You can also ensure that all design teams receive the same materials. If you choose to incorporate the additional design constraint of a budget (described in the Extensions section of this guide), assembling kits in advance will simplify tracking the budget.

Set up the classroom

Team work area
Set up the classroom for student laboratory work in teams. Each pair of students should have a clear work area near an electrical outlet (for the glue gun) where they can organize their materials and build their designs. A classroom desk or table will do.

Launcher
Set up the launcher in a central location away from walls where students can gather around.

Organize students in teams

If students work in pairs, they will all have the opportunity to engage in all aspects of the activity: design, construction, testing, and recording. You may find that larger teams make it difficult for all students to actually manipulate the materials.

Review Safety Procedures

In the interest of maintaining the safety of the students and of yourself, you should be aware of several safety issues during this activity.

Hot glue guns or glue pots have hot metal surfaces that can burn the skin when touched. Show students which areas are hot and advise them to be careful. The hot glue itself also can be painful but is unlikely to cause any serious burn. Nonetheless, students should be warned that the glue is hot.

When launching rockets, students should follow a strict procedure of notifying one another verbally when they are ready to launch and then counting down to the launch. This will ensure that a rocket is not launched when the “catcher” is unprepared.

You may wish to require that the “catcher” wear eye protection.

Cutting a small slit in a tennis ball and then placing the ball onto the end of the launch rod will reduce the possibility of injury from the rod. The tennis ball “bumper” has several drawbacks: It acts as a brake on the rocket and makes for a less exciting launch, If the tennis ball is too secure, the rocket may bounce off of it making it difficult to catch.

Teaching Strategies for an Engineering Design Challenge

Like any inquiry-based activity, this engineering design challenge requires the teacher to allow students to explore and experiment, make discoveries and make mistakes. The following guidelines are intended to help you make this activity as productive as possible.

- Be sure to discuss the designs before and after testing. Discussing the designs before testing forces students to think about and communicate why they have designed as they have. Discussing the designs after testing, while the test results are fresh in their minds, helps them reflect on and communicate what worked and what didn't and how they can improve their design the next time.
- Watch carefully what students do and listen carefully to what they say. This will help you understand their thinking and help you guide them to better understanding.
- Remind them of what they've already done; compare their designs to previous ones they've tried. This will help them learn from the design-test-redesign approach.
- Steer students toward a more scientific approach. If they've changed multiple aspects of a design and observed changes in results, ask students which of the things they changed caused the difference in performance. If they aren't sure what caused the change, suggest they try changing only one or two of the aspects. This helps them learn the value of controlling variables.
- Be aware of differences in approach between students. For example, some students will want to work longer on a single design to get it "just right." Make it clear that getting the structure designed, tested, and documented on time is part of the challenge. If they don't test a lot of models, they won't have a story to tell at the end. Remind them that engineers must come up with solutions in a reasonable amount of time.
- Model brainstorming, careful observation, and detailed description using appropriate vocabulary.
- Ask open-ended "guiding" or "focusing" questions. For example: "How does the force get from the launch lever to the rocket?" or "What made this design stronger than another?" Keep coming back to these questions as the students try different designs. Encourage students to address these questions in their journals.
- Require students to use specific language and be precise about what they are describing. Encourage them to refer to

a specific element of the design (column, strut, joint, brace, etc.) rather than "it."

- Compare designs to those of other groups. Endorse borrowing. After all, engineers borrow a good idea whenever they can. However, be sure that the team that came up with the good ideas is given credit in documentation and in the pre-test presentation. Borrowing should also be documented in students' journals.
- Emphasize improvement over competition. The goal of the challenge is for each team to improve its own design. However, there should be some recognition for designs that perform extremely well. There should also be recognition for teams whose designs improve the most, for teams that originate design innovations that are used by others, for elegance of design, and for quality construction.
- Classify designs and encourage the students to come up with their own names for the designs to be used in the class.
- Encourage conjecturing. Get students to articulate what they are doing in the form of "I want to see what will happen if…"
- Connect what students are doing to what engineers do. It will help students see the significance of the design challenge if they can see that the process they are following is the same process that adult engineers follow.

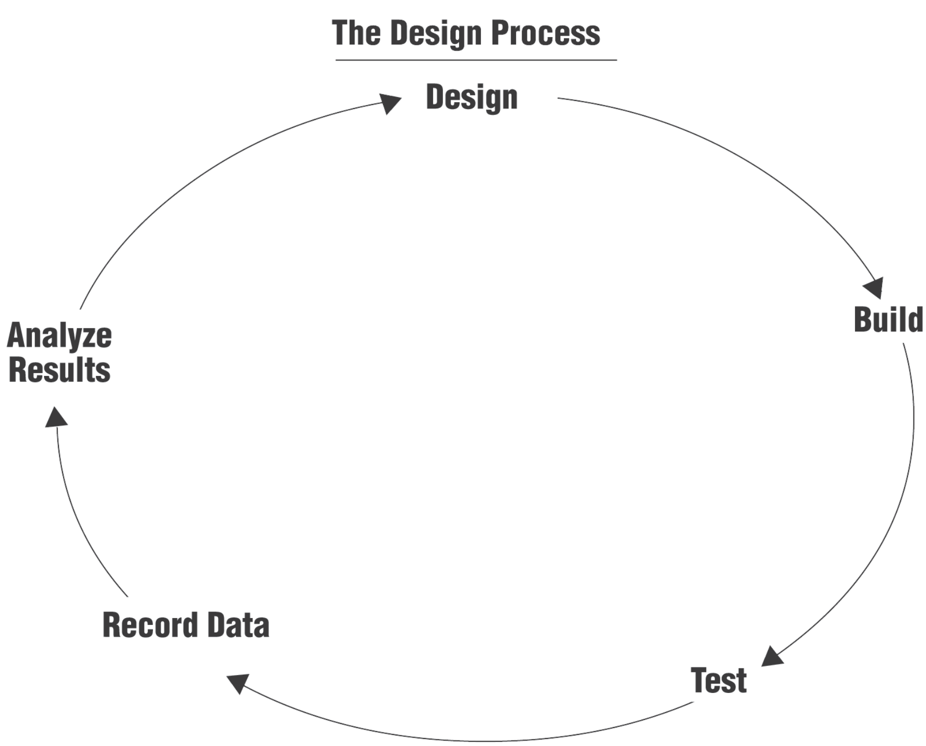
Helping Students Understand the Design Process

Engineering involves systematically working to solve problems. To do this, engineers employ an iterative process of design-test-redesign, until they reach a satisfactory solution.

In the Engineering Design Challenges, students experience this process. To help students visualize the cyclic nature of the design process, we have provided a chart that you can use in a class discussion.

Once students have sufficient experience in designing, building, and testing models, it is valuable for them to formally describe the design process they are undertaking. Students require a significant amount of reinforcement to learn that they should study not just their own results but the results of other teams as well. They need to realize that they can learn from the successes and failures of others, too.

Select a time when you feel the students have had enough experience with the design process to be able to discuss it. Use the black-line master of “The Design Process” to make an overhead transparency. Project it on a screen. Then, using it as a guide, go through the process step-by-step, using a particular design as an example. It’s useful to hold up the model and point out specific features that may be the result of studying the test data or unsuccessful builds or additional research. For example, using a particular model, ask “How did this feature come about? Where did you get the idea? Was it the result of a previous test, either done by you or by another team?”



Note: This chart appears as a black-line master in the back of the guide.

Session 1

Introducing the Challenge and Getting Started

In this first session, you will introduce the activity and provide students with background information about NASA, TIMED, STEREO, Solar-B, and spacecraft structures. You will define the challenge and discuss how engineers approach a design problem. Students will practice dropping the sandbag until they can consistently launch the bottle rocket to orbit. You will conclude the session by launching a teacher-built model thrust structure and challenging students to build models that are lighter-weight.

Learning Goals

- Understand the requirements for the structure of a reusable launch vehicle
- Understand and define thrust structure
- Recognize the need for models
- Understand the relationship between a model and the actual object being designed
- Recognize a need for a standard test procedure
- Make observations and collect data
- Understand the need for averaging
- Calculate averages

The Design Challenge

Students will build an air pressure launcher and a model rocket. The model rocket should be as light as possible yet strong enough to withstand the load of a “launch to orbit ” three times.

Students first determine with different variables the amount of force needed to launch the model rocket. Then they design, build, and test their own structure designs. They revise their designs over several design sessions, trying to maintain or increase the strength and reduce the weight of their structure to determine which variables give the rocket the best or farthest distance down range. They document their designs with sketches and written descriptions. As a culmination, students compile their results into a poster and present them to the class.

1. Introduce the unit

Elicit students' knowledge of the Space Shuttle and spacecraft in general. Use the background information in the previous section, and pictures, video, or models of the Space Shuttle to introduce the concept of a reusable launch vehicle. Introduce the http://stp.gsfc.nasa.gov and http://lws.gsfc.nasa.gov websites to your students. Ask about what needs to be considered in designing a vehicle that must get into space and return to Earth. Discuss the significance of mass (optional: discuss the difference between weight and mass). Explain to students that they will take on the role of engineers for this unit. They will attempt to solve a problem that NASA engineers are working on as they develop the "new" Space Shuttle: designing a lightweight but strong thrust structure for the vehicle.

2. Introduce the challenge

Bring out the launch stand and choose a student to be the catcher. Launch a rocket but drop the weight so that the rocket barely moves. Ask students to identify which parts of the rocket each part of the model represents. The lever is the "engine" providing the thrust, the sandbag weight represents the energy of the engines, and the bottle is the body of the spacecraft.

Explain to students that the thrust structure is the part of the spacecraft's skeleton that holds the engine on to the rest of the vehicle. Use the "Thrust Structures" master to compare the Titan rocket thrust structure to the bottle rocket thrust structure. Explain that, unlike the demonstration in which the bottle "rocket" gets one big push from the lever "engine" and then separates from it, a launch vehicle must be pushed constantly by the engine until it reaches orbit. The push of the engine must travel through the thrust structure to the rest of the rocket.

Define the challenge. Use a transparency made from the master at the end of this guide or post a copy prominently in the room or hand out copies to each team of students.

Explain to students that during the following three class sessions, they will design a thrust structure, launch it, record the results, and then try to improve on the design by making it lighter and stronger. They will get at least four chances to improve on the design. Show students your heavy design, and tell them that you are sure they can do better!

3. Explain the “Culminating Activity”

Explain that each team will spend one class period at the end of the challenge constructing a “storyboard” or poster that will tell the story of the development of their thrust structure. Each team will then make a presentation to the class explaining the evolution of their design, using the storyboard.

The storyboard should contain at least three of the team’s recording sheets. If possible, students should attach three of the actual tested models. The poster should show the evolution of the team’s design from its initial to intermediate to final stages. Essentially, it should “tell the story” of the design process and explain how and why the design changed. It should conclude with a concise statement of “what we learned.”

Direct students to keep running notes, diagrams, questions, research findings, data, etc. in a journal or log in addition to completing the recording sheets. These journals will provide an excellent resource for documenting their experience when they need to make their storyboard.

4. Determine the “engine thrust”

Explain to students that their first task will be to determine the necessary thrust to propel the bottle rocket “to orbit.” They will determine a drop height for the sandbag so that the rocket just flies off the ring stand. Discuss with students why you don’t want it to fly too far off the launch rod. (It would be subjecting the structure to more force than necessary and overshooting “orbit.”)

Choose a volunteer to drop the sandbag and another to catch the rocket. (Launch this rocket without a thrust structure.) Measure the height of the drop with a meter stick or measuring tape or punch a small hole in a file card or piece of manila folder and slide it on a ring stand to mark the height. Have the students start by dropping the weight from a very low height and gradually increase the drop height until the bottle just barely flies off the ring stand.

You might have a different pair of students perform the launch with each increase in drop height. Continue to launch the rocket until students can consistently launch the bottle three times to the desired height. You might want several pairs of students to confirm the height.

When you've determined the optimal drop height, record it and post it in the same place as the challenge. Mark a ring stand at that height with tape or tape the file card onto the ring stand. Optional: use two ring stands and tie a string between them at the drop height.

5. Discuss the results

Ask students: How much mass are we launching to orbit? (1 Kg) What's the source of the propulsive force? (10 Kg bag of sand) What forces are acting on the bag of sand when it's suspended in the air before the drop? (Gravity and the student's muscles) What forces are acting on the bag when it's released? (Gravity) Trace where the force goes. (Down on one side, up from the other end of the lever). Optional: Discuss why it is important for the lever to be stiff rather than flexible.

It is instructive for students to think about how the model bottle rocket and an actual rocket, are the same and different. Here are typical "answers."

6. Demonstrate a poorly designed baseline model

(Note: If time does not allow for this demonstration in this session, it can be left until Session 2, step 6.) In order to provide a baseline model for a thrust structure, you should build one that is truly a juggernaut. For example, use 3-inch lengths of 1/4-inch dowels clustered in threes and attached to cardboard plates on top and bottom using a generous amount of glue. This structure will have a mass greater than 20 grams but will certainly withstand numerous launches. Students will quickly see ways to improve upon this crude design and will take pleasure in building a model that is better than the teacher's.

7. Wrap-up

Show students the craft sticks and the square of cardboard they will use for their first design. Ask them to think about thrust structure designs before the next session.

Session 2

Design 1

In this session, students design and build their first thrust structure using the provided materials. It is important during this session to establish consistent procedures for testing including:

- Pre-test approval of design and recording sheet
- Oral presentation of key design features by students before launch
- Accurate testing and reporting of results on Test Results Sheet
- Post-test discussion of the design and the test results

Learning goals

- Practice construction techniques including use of glue-pot or glue gun
- Recognize the need for clear documentation
- Practice documenting design
- Practice making and recording observations
- Begin thinking about how to make designs strong and light-weight

Materials (Example)

- Launch stand, sand bag, ring stand
- Craft sticks
- Glue guns and glue sticks
- 3-1/2 inch square pieces of cardboard
- Paper cups (optional)
- Transparency and handouts of recording sheets
- Chart paper (or chalkboard) for recording launch results
- A balance or scale accurate to a tenth of a gram
- Overhead projector (optional)

1. Review the design challenge and the design constraints

Make sure students understand the challenge. Use the master to review it.

2. Introduce the materials

Explain to students that they must build a thrust structure using the craft sticks and hot-melt glue. The structure should be attached at the top to a square of cardboard on which the bottle will sit. The structure is not attached to cardboard at the bottom.

3. Review safety issues

Point out to students that the tip of the glue gun and the metal strip at the front of the glue pot are hot and should be avoided. Review the procedure for burns. Remind students to wear safety goggles when launching their model.

4. Introduce the recording sheets

Introduce the Design Specifications and Test Results sheets. One way is to make a transparency of each sheet and project it on the overhead. Tell students that these are where they will record all the details of their designs and the results of their testing. Explain that engineers need to keep careful records. Ask students why record keeping is so important. Discuss each part of the "Design Spec" and "Test Results" sheets. Make sure students understand that one sheet shows their model before testing and that the other shows it after testing.

Remind students to keep track of their designs by numbering their recording sheets. Remind them that they will use their recording sheets to construct a storyboard at the end of the challenge.

Explain to students the importance of a detailed sketch of their design. Their goal in sketching should be that someone looking only at the sketch could reconstruct their design. You may wish to show a completed recording sheet as a sample.

Two sketching techniques to introduce are detail views and section or cutthrough views. A detail view is a separate close-up drawing of a particular portion of the design that may be difficult to show clearly in the drawing of the full design. A section view shows what the design would look like if it were sliced in half. It enables the artist to show hidden parts of the design.

In addition to answering the questions on the design spec sheets, students should also keep running notes, diagrams, questions, research findings, data, etc. in a journal or log. These journals could be as simple as notes taken on the back of the design spec sheet. A journal will provide an excellent resource for documenting the experience when a student needs to make the storyboard.

5. Explain the test procedure

- When their design is completed, the team completes a recording sheet and brings the model and the recording sheet to the teacher.
- The teacher checks the recording sheet for completeness and accuracy.
- The teacher checks that the model has conformed to all design constraints.
- Before their model is tested, each team must do a brief oral presentation for the entire class in which they describe the key features of the design.
- During the testing, the team should carefully observe and record the performance of their design.

6. Students design and build their models

If you did not have time to complete the demonstration of a poorly designed model, do it now. See step 7 in Session 1.

Allow 10–15 minutes for this first design and build. Establish a cut-off time when you will begin testing. Teams that do not have designs ready to test by the cut-off time must wait until the next round of testing.

7. Approving models for testing

When a team delivers their design and recording or data sheet, check the following variables:

- Amount of Air Pressure
- Rocket Design
- Launcher Angle
- The recording sheet completely filled out, including a satisfactory sketch

8. Test the models

Assign a student to record the resutls of each test on a chart or the blackboard or a large sheet of paper. The chart should include the following:

Team	Design #	Protection Time			
		Observer 1	Observer 2	Observer 3	Average

You may also want to include a column for “design strategy” if you choose to classify the designs.

Test each team’s model three times in succession with no repairs allowed between launches. If you have more time, you may wish to increase the number of launches per model. Inspect the model after each launch. Students should make notes about which structural members failed or are in danger of failing.

A failed launch occurs when the rocket does not make it into orbit. A failed launch also occurs when the design no longer meets the design constraints.

9. Discuss the results of testing

The post test discussion is critical to expanding students’ learning beyond the design and construction techniques and connecting their design work with the science concepts underlying their work.

Encourage students to hold the model and use it to illustrate their point when they talk about a particular design feature.

For each model, you should pose the same guiding question:

> “How did this structure transmit the force of launch from the lever to the bottle?”

Other discussion questions might include:

- What happened to each part of the thrust structure during the testing?
- Did any parts of the design seem to fail before the rest? Why?
- Which design features were most effective? What made the designs effective?

Have students trace the path of the force through the structural members. See further discussion of how to do this in the section “Linking design strategies and observations to science concepts.”

Record (or have a student record) the most successful design features on a transparency or on a wall chart. This list should be expanded and revised throughout the activity as the students collectively discover which designs are strong and lightweight.

If any of the columns in the structure have buckled, help students think about how to strengthen the posts, for example, through bracing. Here is an interesting demonstration of buckling: Take a flexible ruler or meter stick. Stand it up on the floor or table. Press straight down on the top end until the ruler begins to bow out or buckle.

Try the same experiment with rulers of different lengths but of the same thickness. Show that any post or column buckles if placed under a sufficient load. But notice that the shorter rulers can support more load without buckling. Then ask a student to grasp and hold steady the middle of the ruler. Repeat the pressure on top with your hand. Show that because the ruler is braced in the middle it is effectively two short columns rather than one long one.
You could also demonstrate the relationship between buckling and the length of a column by using a toilet paper tube and a paper towel tube. Load both with books. The longer one will buckle first. (Make sure they are the same diameter and made of the same thickness of cardboard.)

Sessions 3 and 4

Designs 2, 3, 4 and 5

Using what they have learned from the first design, students revise and redesign their thrust structure in several more design-build-test cycles.

Learning goals

- Distinguish between effective and ineffective design features
- Incorporate design strategies gleaned from experimentation and observation
- Refine observation skills
- Draw conclusions based on analysis of test result data
- Record test data
- Analyze test data and draw conclusions
- Refine understanding of structures and forces

Materials (Example)

- Launch stand
- Craft sticks
- Glue guns and glue
- 2-liter bottles filled with water or sand with guide tubes attached
- 3-1/2 inch squares of cardboard
- Ring stands to be used for static testing

1. Review the previous session

If a day or longer has passed since the previous session, review the results of the first round of testing. Review the successful and unsuccessful design features.

2. Design, build, test, and discuss results

Continue to add successful design features to the list you started on a transparency or chart paper in the previous session. Continue to ask students how the thrust is transferred from the lever to the bottle and to have students trace the load paths on paper or directly on the model. Refer to the science concept links following the session descriptions for connections that can be made between student observations and science concepts.

In the post-test discussion, lead students to make conclusions about the probably success of a thrust structure built of a certain number of craft sticks.

Allow students approximately 15 minutes to design, build, and complete a recording sheet for each model.

3. Introduce static testing

Up to this point the students have been testing their designs by launching them. This kind of testing may destroy the models if they are not strong enough. The models that are "plenty strong enough" will not be destroyed, but models that are just a little bit too weak may be damaged in testing. This is unfortunate because the student may have to start over from scratch, whereas if the model were still intact, it might be possible to make some minor change that would make the model strong enough to survive three launches. As the students get closer and closer to their optimum designs (as lightweight as possible, but still strong enough), they should become more attuned to the need for non-destructive testing before actual launch. You might refer to this as pre-testing or static testing.

Introduce this section by asking the class whether they think it would be desirable to have a way of testing the models that would not destroy those that were just a little bit too weak. Point out, if you wish, that engineers prefer non-destructive testing of their designs whenever possible. Ask students to think of non-destructive ways they could test their models that would give them information about the model's strength, but would not destroy the model suddenly as sometimes happens during a launch.

They will probably come up with ideas of squeezing the model, compressing it, or somehow applying a load to it gradually. The problem, of course, is that they don't know how much to squeeze or how much weight to load onto the model because they don't know how much compressive force the model experiences at launch. There are several ways you might determine the compressive force at launch. Here are two approaches:

(1) Build a thrust structure model that will deform, launch it, look at the deformation, and then load up an identical model with enough weight to achieve the same deformation. For example, glue a paper cup onto the cardboard square. Launch a bottle "to orbit" using this thrust structure. Note the amount of deformation (crushing) of the cup. Take a second paper cup thrust structure and load it up with enough weight to achieve the same deformation. Note the amount of weight. This is the static weight any thrust structure must withstand at launch. If a student model withstands this amount of weight (and maybe a bit more), then it should be able to survive launching.

(2) A second way to figure out how much weight a model needs to be able to support is to build a test model that is exactly strong enough for launch and then to see how much weight it can support. For example, using paper cups for the thrust structure, see if a single cup can withstand the force of launch to orbit three times. If it cannot, then add a second cup, nested onto the first. See if two cups can withstand launch force. If not, then add another cup. When you finally have enough cups to withstand three launches, you have an adequate thrust structure. Then see how much weight this model can support. Any model that can support the same weight or more should be able to survive the force of launch. You can use a table like the one below to record the results of gradually strengthening the paper cup thrust structure.

The static weight that causes the structure to fail is the weight to use in future static tests. If a design can support that weight, it should be able to withstand three launches to orbit.

Ask students what they would look for in a static test. Here are some possible ideas:

- Structural members buckling
- Glue joints loose or unstable
- Entire structure unsteady when moved slightly side to side

Remind students that they should record the results of static testing directly on their "Test Results" sheet or in their journal for

use in creating their storyboard.
You can lead from this introduction of static testing into a discussion of the similarities and differences between static and dynamic loads. Refer to the Linking to Science Concepts section for a more detailed description of the concepts involved.

Loading static weight onto a thrust structure will be easy if you use the bottle rockets themselves as the weights and use the ring stand to steady them. Place the thrust structure on the base of the ring stand, slide the bottle's brass sleeve onto the ring stand, and lower it gently onto the structure. Add more bottles as needed. They should stack up nicely, held in place in a vertical stack by the ring stand. If you need more weight than you can obtain using bottles of water, fill some bottles with sand. You can use bottles of different sizes and filled to different levels with sand in order to create a set of weights. Of course, you will need to determine the weight of your "weights," and this, in itself, is an interesting exercise for the students to carry out. To make static testing easy and accessible to the class, set up a "static test stand" permanently in the room. Then you will have a static test stand and a dynamic test stand.

Session 5

(Recomented for Highschool)

Construct a Storyboard/Poster

As a culminating activity, each team creates a “storyboard” poster that documents the evolution of their thrust structure designs from initial to intermediate to final stage. The storyboard provides students with a way of summarizing and making sense of the design process. It provides opportunities for reflection and enables students to see how their design work has progressed from simple to more sophisticated and effective designs.

Learning goals

- Summarize and reflect on results
- Organize and communicate results to an audience

Materials

- Posterboard or large sheets of paper approximately 2’x3’, one per team
- Markers, crayons
- Plastic sandwich bags for holding tested models
- Glue or tape for attaching recording sheets and tested models to storyboard

1. Explain the assignment

Explain to students that they will create a poster or “storyboard” that will tell the story of their thrust structure design. Explain that professional conferences usually include poster sessions at which researchers present the results of their work.

The storyboard should include recording sheets, tested models, and any other artifacts they think are necessary. The storyboard should include a brief text that describes how their design evolved through at least three stages: beginning, intermediate, and final. If students have kept journals during the design process, they should use some of the notes from their journals on the poster.

Students may attach their completed recording sheets or re-copy the information onto the storyboard. They should attach the actual tested models if possible. Placing the model in a plastic bag and attaching the bag to the poster works well.

2. Define the assessment criteria

Explain to students that their storyboards will be evaluated on the following criteria:

- A clear storyline, organized to show the development of the design
- Shows at least three designs
- Contains clear sketches with key features identified
- Includes test results and description of what happened to the design during the tests
- Includes conclusion about the most effective thrust structure design and why it is effective
- Uses scientific vocabulary
- Has an appealing layout with a title
- Uses correct grammar and spelling

You may optionally assign additional research or invite students to do research on their own initiative. Research findings could also be included on the storyboard. See the Resources section for suggested starting points. Students could investigate:

- Internal structure used in rockets
- Internal structure used in other devices and vehicles
- Load bearing properties of materials

3. Create the storyboards

Give students an entire class session to create their storyboards. You might take this opportunity to encourage students to practice sketching detail and section views of the models as described in Session 2.

You might also want to assign several students to prepare a "results" poster for the entire class. This poster would make use of the charts on which you recorded data from each test session. The overall improvement of the class could be calculated and displayed.

Session 6

(Recomended for Middle & High Schoolers)

Student Presentations

When all storyboards have been completed, put them on display in the classroom. Allow students time to browse among the posters. Encourage conversation. Then reconvene the class and allow each team a few minutes to present their storyboard.

Another option is to conduct a poster session as might occur at a professional conference. Half the teams would remain with their posters to answer questions while the other teams browse. After about 15 minutes, the browsing teams stand by their posters while the other teams browse. Browsing teams should ask questions and engage the presenting teams in conversation.

The poster session provides an opportunity to invite parents, other teachers, and students from other classes in to view student work.

Learning goals

- Communicate results to an audience

Linking design strategies and observations to science concepts

An important opportunity for science learning through this Engineering Design Challenge comes from the connections that students make between their design solutions, their observations, and the underlying scientific principles. As you observe students designing, as you conduct the testing, and as you discuss the test results, there will be numerous opportunities to draw connections between what the students are doing and the science principles of motions and forces. This section provides suggestions and background information to help you draw those connections at the moment they arise, the "teachable moment," when students are highly engaged and receptive to new information. This section is organized according to observations the students might make and design strategies they might employ.

Observation: Tracing the Path of the Force

Students should be able to trace the path of the force from the lever through their structure to the bottle. They can do this simply by pointing out the path the force will take or by drawing a sketch with arrows showing the direction of the force. They can also color the structural members in the model. This will provide an opportunity to discuss the advantages of distributing force over a wide area.

Design Strategy: Balanced loads

Students should recognize that evenly distributed support will evenly divide the force of launch. You might point out that the bottom of the bottle is axially symmetric and that there must be a reason for that design. Ask students to think about why many structures in the natural world, as well as the "built world" are symmetrical. Perhaps it has to do with balanced loads.

Observation: Compressive Forces

As students think about the forces on their model, they will realize that the main force on it during launch is compression, the direct result of the bottle pressing down and the lever pressing up on the thrust structure. Thinking about these compressive forces offers an opportunity for learning more about what's actually going on before, during, and after launch. Before launch, as the thrust structure and rocket rest on the launch lever, the forces are balanced and, therefore, there is no acceleration. During launch, there clearly is acceleration, and, therefore, there must be unbalanced forces on the thrust structure and the rocket because they accelerate. After launch, there is, again, acceleration (or deceleration, depending on the frame of reference) as the rocket gradually slows down and stops at its apogee. So, there must be unbalanced forces causing this acceleration. Acceleration would continue (downwards) if the catcher did not catch the rocket and prevent it from falling.

If students have done static testing, they will have an idea of the amount of force exerted on the thrust structure during launch. This will be the weight that they determined the thrust structure had to support. This is the force that the bottle experiences during launch. Using F=ma, they can calculate the acceleration the bottle experiences. This is the so-called "g-force."

Squeezing a thrust structure

If each hand in the diagram presses on the thrust structure with a force of 1 Newton (1 N), then the compressive force the launch structure experiences is 1 N.

When forces of equal strength are exerted on opposite sides of an object, the compressive force on the object is the size of one of the equal forces. The object does not accelerate because the forces on it are balanced.

Forces on the thrust structure

When the thrust structure rests by itself on the lever, there is no compressive force on the structure. The structure presses down on the lever with a force equal to its weight—say 0.1 N, and the lever exerts a matching force of 0.1 N upwards on the structure. There is a force pressing up on the bottom of the structure, but no force pressing down on its top, so there is no compressive force on the whole thrust structure.

Note: The thrust structure's weight does create a compressive force on the individual elements that make up the structure, because every piece of the structure (except the top) is pressed down by the parts of the structure above it and supported by the parts below it. The very bottom of the thrust structure experiences a compressive force equal to the structure's weight. In very heavy objects like skyscrapers, this internal compressive force is very important to the design of the building. The weight of a thrust structure is so small compared to the compressive forces due to launching a bottle, however, that we can ignore the internal compressive forces due to the structure's own weight.

When an object rests on a surface, there is no compressive force on the whole object. (We are not concerned with the internal compressive force due to the object's own weight.)

If a "rocket" presses down on a thrust structure with a force of 9.8 N (without breaking it), the structure transfers this 9.8 N force to the lever supporting it. The structure also continues to push down on the lever because of its own weight of 0.1 N, so the total force the thrust structure exerts on the lever is 9.9 N. The lever pushes back with a force of 9.9 N. The compressive force on the structure is 9.8 N, the amount of force it experiences from both directions at once. (The extra 0.1 N comes only from below, not from above, so it does not contribute to the compressive force on the structure.)

When a force is exerted down on an object that is resting on a surface, the compressive force on the object is the size of that downward force.

Forces during acceleration

If you were to use the launch lever to launch the thrust structure behind a toy car horizontally, you would need to push hard enough to make both the structure and the car accelerate forward. The structure transmits to the car some of the force exerted by the lever. The car pushes back on the structure with the same amount of force.

If the structure accelerates, that means that the forces on it must be unbalanced. That is, the forward force exerted by the lever (say, 2.5 N) must be stronger than the backward force exerted on the structure by the car (say, 1.5 N).

The compressive force on the structure is the amount of force exerted on it from both directions, or 1.5 N. The remaining 1.0 N of the force exerted by the lever went into accelerating the structure and the car. Compare this situation to the bottle sitting on the thrust structure: while a non-accelerating object (that is not deformed) transmits all of the force exerted on one side of it to the object on the other side of it, accelerating objects transmit only some of the force exerted in the direction of their acceleration.

When forces of different strengths are exerted on opposite sides of an object: the compressive force on the object is the size of the smaller force; and the object is accelerated by the difference between the two forces (also called the net force on the object).

Observation: Static and Dynamic Loads

Students should recognize that the amount of time a force is applied matters. When launching the bottle, the force is applied for a very short time. This is called a dynamic load. When static testing, the force is applied for a relatively long time. A load applied slowly is called a static load. Salvadori's book Architecture and Engineering contains many excellent activities for investigating forces including the following.

Pour sand into a jar on a scale and stop when the weight of the sand is one kilogram. If the jar weighs 0.25 kg, the total static load on the scale is 1.25 kg. Now hold the filled jar just above the scale and release it suddenly. The scale hand will show a maximum of about 2.5 kg. Repeat the experiment and ask students to follow the scale hand carefully to determine its maximum position. Notice that the scale measures approximately twice the weight of the filled jar. This is the dynamic load on the scale.

There are many practical instances where the time that a force is acting makes a big difference. For example, impact barriers are designed to exert a small force over a long time in order to stop a vehicle more gently than hitting a wall. A baseball player brings in his arms as he catches a ball in order to cushion the ball and bring it to rest more slowly. Boxers “roll with the punch” in order to increase the contact time of the glove with their body and absorb the punch more gradually. Tennis players and golfers “follow through” in order to increase the time that the racket or club is in contact with the ball.

Observation: Tension

If students construct a band around the columns to keep the columns from buckling outward, the members of the band will be in tension during the launch. Point out to students the difference in the performance of the craft sticks under tension (the sticks are extremely resistant to breaking when a pulling force is applied to the ends) and under compression (as described in the section above). Have the students color their models using one color for members under compression and another color for those members under tension.

Design Strategy: Strong posts

To overcome the tendency of vertical posts to buckle, students might make them stronger by doubling or tripling sticks. This, of course, increases the weight.

Design Strategy: Bracing

Another strategy to overcome buckling is to add a crossbrace. The brace might be a band around multiple columns or a diagonal piece from the midpoint of a column to the base. Such a brace effectively divides the column into shorter columns which have less tendency to buckle.

Design Strategy: Solid joints

Designs that fail at the joints may simply need more glue. They also may not be carefully aligned, with the result that the force is applied entirely to one member at the joint rather than evenly to all the members at the joint.

Understanding Energy Transfers During Launch

One of the many ways to understand what happens during launch of the bottle rocket is to analyze the energy transfers that take place. After students have had experience building thrust structures and using them to launch bottle rockets, take time out to discuss with them the energy transfers going on during a launch. Make an overhead transparency from the master page "Testing a Thrust Structure" and project it where the entire class can see it.

In order to engage in this exercise, students need some basic understanding of energy as the ability to do work. It also would be helpful if students have had a prior introduction to gravitational potential energy and to kinetic energy.

While looking at the overhead transparency, review what happens during a launch. (Sandbag falls, lever moves, pushes thrust structure, which pushes rocket, rocket rises, reaches apogee, and gets caught.)

Then ask students whether energy is needed to launch the bottle rocket. (Yes!)

Next, ask them to explain where the energy for the launch comes from. They may say, "From the sandbag." If so, probe further by asking:

- How does the sandbag have energy? (By virtue of its position.)
- How does it get its energy? (From the pull of gravity on it.)
- Does it have energy when it is sitting on the ground or only when it is held aloft? (It has useful energy with respect to the launch lever only when it is held aloft. Of course, it has energy in its atomic structure all the time, but we are not concerned with that kind of energy here.)
- Would it have more energy if it were more massive? (Yes.)
- Would it have more energy if it were held higher? (Yes.)
- Where does the energy come from that moves the sandbag from the floor to its position above the launch lever? (Human muscles, which are powered by chemical reactions.)
- Would the sandbag have the same energy if it were positioned the same height above the surface of the moon? (No, because the gravitational field of the moon is less than that of the earth. It would also take less muscular effort to lift the sandbag into position on the moon. An interesting question is: If you replicated the whole launch on the

moon would the bottle rocket rise to the same height? What would be different on the moon? What would be the same?)

- What do we call the kind of energy that the sandbag has due to its position? (Gravitational potential energy, abbreviated PE.)

Then ask, “How does the sandbag transfer energy to the thrust structure and the rocket?”

Students may be able to explain that as the sandbag falls it loses height and simultaneously accelerates. It gains kinetic energy and loses potential energy. When it hits the launch lever, some of its kinetic energy is transferred to the lever, which transfers energy to the thrust structure. The thrust structure accelerates and gains kinetic energy. It pushes on the bottle, which accelerates and also gains kinetic energy. The bottle rises and as it does so, it slows down and reaches a maximum height of about one meter. (It slows down because gravity decelerates it.) At its apogee (highest point) it has no kinetic energy and has its maximum gravitational potential energy.

For students in grades 6 – 8, this explanation of energy transfer may be sufficient. However, students in ninth grade may be able to use an easy formula to calculate gravitational potential energy.

Students can then go on to consider kinetic energy. They can calculate the kinetic energy and velocity of the sandbag and the kinetic energy and velocity of the bottle after launch. This is discussed in the section that follows.

Modifications and Extensions

Changing the cardboard plate

The thrust structure model has been tested in a number of permutations with satisfactory results. The challenge seems to have the optimal level of difficulty when only one cardboard square is used, at the top of the structure. However, you may wish to use an additional piece of cardboard on the bottom of the structure. This will make the structure stronger but will make it more difficult to see the results of specific loads on the structural members. You may also wish to use a different shape, size, or thickness of cardboard or give students the option of modifying the cardboard. Doing away with the cardboard altogether will make the challenge much more difficult.

Allowing repairs

If students discover the beginning stages of a design failure before they have successfully launched three times, they can be allowed to stop testing and repair their design. A team electing to repair its design should go to the end of the testing queue. The team should also weigh its model again before testing, record the new weight, and record the design changes on the Design Spec Sheet.

Increasing the rocket mass

You may find, especially with advanced students, that students reach a plateau in reducing the weight of their structure. At this stage, you may want to add additional design constraints to increase the challenge. The most obvious modification would be to add mass to the rocket.

Limiting designs by cost

Ask students to brainstorm about what NASA engineers must do to reduce the cost of getting to space. Holding up a model of the space shuttle or referring to a poster will be useful in stimulating student ideas. You might want to discuss such facts about the Space Shuttle as how much fuel it uses, which parts are reusable and which are not, etc. Possible answers include: Make sure all the parts can be reused, make the vehicle lighter so it uses less fuel, use less expensive materials, make it more durable so you don't need to do much to it to prepare for the next launch, make a better engine that uses less fuel, make the engine more powerful so you can carry more on a single launch, use less expensive fuel. Students are less likely to come up with process ideas for cutting costs such as designing faster and testing more efficiently.

Assign a cost to each material and start students with a set budget. Allow students to purchase materials. You may also attach a cost to testing each design. Students must stay under budget while designing the thrust structure model. Compare designs from teams on the basis of weight and cost. Have students find the ratio of cost to weight for each design and plot the results on a graph.

Designing with additional materials

You may come up with your own ideas. If you are constraining designs by a budget, you will want to assign different costs to different materials.

Resources

About Heliophysics Projects Division

http://stp.gsfc.nasa.gov
http://lws.gsfc.nasa.gov
http://stargazers.gsfc.nasa.gov

About the Space Shuttle

http://www.nasa.gov/qanda/space_shuttle.html
NASA Facts On Line, John F. Kennedy Space Center
http://www-pao.ksc.nasa.gov/kscpao

About Space Vehicles

International Reference Guide to Space Launch Systems. Steven J. Isakowitz. AIAA Press, Washington, D.C., 1995.

The History of Developing the National Space Transportation System. Second Edition. Dennis R. Jenkins. D.R. Jenkins, Harbor Beach, Fla., 1996.

Stine, G. Harry. Halfway to Anywhere: Achieving America's Destiny in Space. NY. M. Evans and Co. 1996.

Stine, G. Harry. Handbook of Model Rocketry. NY. Prentice Hall Press. 1987.

About New Space Vehicles

"A Simpler Ride Into Space" by T.K. Mattingly. Scientific American, October 1997, pp. 121-125.

"The Way to Go in Space" by Tim Beardsley. Scientific American, February 1999, pp. 80-97. Further reading: www.sciam.com/1999/0299issue/ 0299beardsleybox1.html

About the Space Shuttle Structure

Introduction to the Space Shuttle: Shuttle Systems
http://www.ksc.nasa.gov/shuttle/technology/sts-newsref/sts_coord.html#sts_body

About Engineering and Careers

www.discoverengineering.org

A new web site, Discover Engineering Online, lets adolescents investigate a host of engineering achievements. Aimed at inspiring interest in engineering among America's youth, the site is a vast resource. Among the many features of the site is information on what engineers do and how to become one. Designed specifically for students in grades six through nine, the site has links to games, downloadables, and powerful graphics, as well as to web sites of corporations, engineering societies, and other resources. One section, for example, lists several "cool" things tied to engineering, such as the mechanics of getting music from a compact disc to the ears of a teen, how to make a batch of plastic at home, or learning how to fold the world's greatest paper airplane.

http://spacelink.nasa.gov/Instructional.Materials/Curriculum.Support/Careers/.index.html

About Design Challenges

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About Physics

Hewitt, Paul. Conceptual Physics.

About Structures

Macaulay, David. Castle.
Macaulay, David. Cathedral, the story of its construction.
Macaulay, David. City: A Story of Roman Planning and Construction.
Macaulay, David. Mill.
Macaulay, David. Pyramid.
Macaulay, David. Unbuilding.
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CD-ROMs about Space Transportation

Space Transportation: Past, Present and Future
Available from NASA Marshall Space Flight Center
An Interactive Guide to the X-34 Program's History, Technology & Achievements
Available from NASA CORE
Venturestar: The Odyssey Begins
Available from Lockheed Martin

Some NASA Web Sites

http://spacelink.nasa.gov
An Aeronautics and Space Resource for Educators

http://core.nasa.gov
The worldwide distribution center for NASA-produced multimedia materials

http://education.nasa.gov
A link to the many education resources provided by NASA

http://www.nasa.gov
NASA home page

http://www.dfrc.nasa.gov/
Dryden Flight Research Center Home Page

http://www1.msfc.nasa.gov/
Marshall Space Flight Center Home Page

NASA Engineering Design Challenges

Dear Parent:
Your child is beginning an exciting unit in science class entitled the NASA Engineering Design Challenge. This unit will connect students with the work of NASA engineers by engaging them in a related design challenge in their classroom. Students will design, build, and test their own solutions to a design problem similar to one faced by NASA engineers.

The Challenge

Your child's challenge in class is to build a thrust structure for a model of a rocket that can withstand the force of three launches. The structure will be built from such common materials as craft sticks, cardboard, and glue. The design will be tested and then the student will have the opportunity to revise the design based on the test results. Designs will go through a number of revisions to try to reduce the weight and increase the strength of the thrust structure. As a culminating activity, students will create posters documenting their design process and results.

Questions to ask your child about the project

This is an inquiry-based activity. This means that much of your child's learning depends on hands-on experimentation. It's important, however, that your child reflects on the hands-on work and tries to understand why certain design features were or were not successful. You can encourage this reflection by asking your child about the activity. Ask your child to:

- Explain the challenge and the design constraints.
- Describe the design and how it survived the testing.
- Explain why the design did or didn't work well.
- Explain whether other students in the class tried different designs and how those designs tested
- Explain the next design and why it will be an improvement.

Some Activities to do at Home

There are many examples around home of structures in action.

- The building you live in is held up by a structural skeleton.

If you can, show your child some of the framing elements of your home. Perhaps by going to the basement or attic you can see some of the house framework more clearly. In the basement you can probably see posts (columns), joists,

flooring, and other members. You may well see diagonal braces fastening the floor joists to the subflooring. Discuss with your child how each of these elements contributes to the support of the house.

• Discuss with your child what kind of structural support is behind the walls, e.g. studs. Point out walls that are "load-bearing" vs. walls that are not. If you have done any remodeling lately you may have had to address structural issues with the architect or carpenter. Discuss these with your child.

• The structure of a garage is often easier to see than that of a house because the studs, rafters, and other structural members may be left exposed. Perhaps you can measure the distance between studs and discuss why they are spaced as they are. If the garage has a gable roof, discuss the cross-ties that keep the roof from pushing out the walls that it sits on.

• Houses or buildings in the neighborhood that are under construction may reveal their structure more easily than an already-built house.

• The furniture in the house has a structure. Tables and chairs are supported by legs that are essentially columns. You can examine tables and chairs to see how the designer made them stronger by adding cross-braces and other supports.

• If there are any radio or TV towers nearby, point out how they are stabilized by the addition of guy wires (if they are). You may also see guy wires stabilizing home antennas. The guy wires are examples of structural elements that are strong while pulled taut. This is called “being in tension.” The antennas may also show how cross-bracing is used to make a structure stronger.

Resources for Further Exploration

About the Space Shuttle
http://www.nasa.gov/qanda/space_shuttle.html

NASA Facts On Line, John F. Kennedy Space Center
http://www-pao.ksc.nasa.gov/kscpao

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http://www.nasa.gov
NASA home page

http://www.dfrc.nasa.gov/
Dryden Flight Research Center Home Page

Learn about the X-33 and other "X-planes." Includes a photo gallery of more than 1,000 digital images of research aircraft

http://www1.msfc.nasa.gov/
Marshall Space Flight Center Home Page

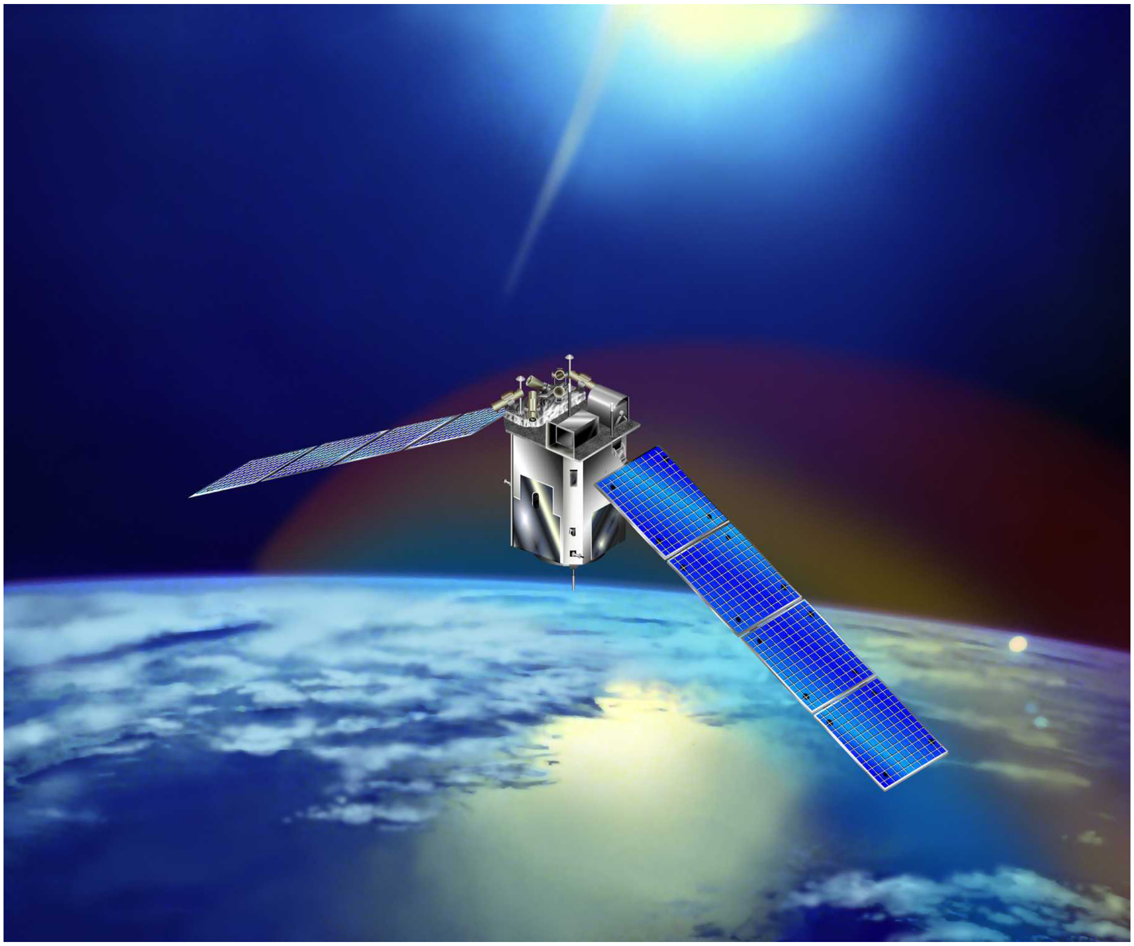
http://stp.gsfc.nasa.gov
Solar Terrestrial Probes Program

http://lws.gsfc.nasa.gov
Living With a Star Program

http://stargazers.gsfc.nasa.gov
Solar Terrestrial Probes/Living With a Star Education and Public Outreach Website

http://en.wikipedia.org
Free encyclopedia

TIMED



STEREO

Solar-B Launching

Design Number

Design Specifications Sheet

Date:________________ **Class:**______________________ **Team:** ____

Designer Names:____

Sketch your design below. Identify materials used. Show glue points.

Describe the key features of your design

Test Results Sheet

Design Number

Date:__________ **Class:**__________ **Team:** __________

Designer Names:__________

Sketch your model below after testing. Show failure points if any.

Record the test results

Test **Result**

1__________

2__________

3__________

Describe the results of the testing. Explain which features seemed effective and which did not.